Renewable and Sustainable Energy Reviews 35 (2014) 171–182

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# Free cooling of data centers: A review

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ARTICLE INFO

*Article history:*
Received 29 May 2013
Received in revised form
20 February 2014
Accepted 7 April 2014
Available online 22 April 2014

*Keywords:*
Free cooling
Data center
Airside economizer
Waterside economizer
Heat pipe

ABSTRACT

The growing demand for electricity and the increasing size of the carbon footprint of data centers worldwide bring a severe challenge to sustainable development of human civilization. The cooling energy consumption takes up around 30–50% of the total consumption of data centers due to the inefficient cooling system. Free cooling is an effective solution for reducing the power consumption of cooling systems. This paper reviews the advancements of data center free cooling mainly focusing on configuration features and performances. Three kinds of free cooling methods, airside free cooling, waterside free cooling and heat pipe free cooling are discussed and performance characteristics of each are analyzed. Further, the criteria of performance evaluation for free cooling of data centers are summarized, and an overview of free cooling systems based on these criteria is demonstrated in order to help researchers acquire the latest developments in this area.


**Contents**



## 1. Introduction

Ever since the third industrial revolution, the rise of information technology (IT) has brought great reform to human life. Data centers, which include all the buildings, facilities, and rooms that contain data servers, telecommunication equipment, cooling equipment and power equipment [1], are developing quickly as an important part of IT industry [2,3]. However, increasingly serious energy crisis comes with the rapid expansion of the number of data centers. Electricity used by data centers worldwide doubled from 2000 to 2005; Even though the 2008 financial crisis caused economic slowdown, this number increased by about 56% from 2005 to 2010 [4]. In 2010, total electricity used by data centers was of about 1.3% of all electricity use for the world. For US, it was 0.12% in 2000 [5] and 2% in 2010 [4].

As mentioned above, cooling equipment is one of the main facilities in data centers. Data centers must be adequately cooled

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http://dx.doi.org/10.1016/j.rser.2014.04.017
1364-0321/

**Nomenclature**

| | |
|---|---|
| $Q$ | heat dissipation (W) |
| $Q_{con}$ | heat dissipation of condensation(W) |
| $Q_{exp}$ | heat dissipation of evaporation(W) |
| $Q_{pcm}$ | heat stored in phase change material(W) |
| $Q_w$ | heat stored in water(W) |
| $T_a$ | ambient temperature (°C) |
| $T_e$ | enclosure temperature (°C) |

*Abbreviations*

| | |
|---|---|
| BMS | battery management system |
| COP | coefficient of performance |
| CRAC | computer room air conditioner |
| CRAH | computer room air handler |
| DX | direct expansion |
| IACT | Integrated air conditioner with thermosyphon |
| IT | information technology |
| PCM | phase change material |

because heat dissipation has become a major determinant factor of availability and reliability. Traditional cooling equipment of data centers is a computer room air conditioner (CRAC) based on mechanical vapor compression refrigeration. Its energy consumption takes up around 30–50% of the total consumption of data centers [6–8]. An example of data center energy split is shown in Fig. 1 [7].

Traditional cooling system consumes a large quantity of energy due to three main reasons:

(1) High energy consumption of cold source. Traditional vapor compression system needs to work all the year round, even at night or in winter when the temperature is low.
(2) Large energy consumption in piping system. A lot of energy is used by pumps and fans to transport cold water or air. Meanwhile, long distance transportation results in a loss of cold source.
(3) Mixing of cold and hot air streams. Entrainment of the hot air into the cold aisles is widely seen due to the lack of airflow control devices [9].

We can improve the efficiency of the cooling system from these three aspects. For the second and third aspects, control methods proposed by scholars include utilizing frequency conversion fans [10], ceiling coolers [11] and rack backdoor coolers [12], optimizing the structure of perforated tiles [13–16], relative position of racks [17,18] and mode of supply and return air [19–21]. For the first aspect, free cooling technology is an ideal solution.

Free cooling, which is commonly known as economizer cycle, involves using the natural climate to cool the data center as opposed to the more traditional method of using conventional systems such as air-conditioning [22,23]. That is, when the outside air (or water) is cool enough, it can be used as a cooling medium or the direct cold source of data centers. For the vast majority of regions, the outdoor temperature is lower than that of the data center in a long period of the year. When the outdoor temperature is sufficiently below the data center temperature, the heat will naturally flow to the outside without the need of the “temperature boost” provided by the compressor and the vapor-compression refrigeration system, so its function is unnecessary. Therefore, under favorable conditions, the compressor can be bypassed, which can save energy significantly. When the compressor is bypassed, economizers are used to utilize natural cold source. Two categories of economizers are in use currently, waterside economizer and airside economizer. In recent years, a new kind of free cooling system, heat pipe cooling system, has been developed and come into service.

For a long period, free cooling application in data centers was restricted because the environment demands of data centers were so harsh that the outside environment was not appropriate for free cooling in most time in a year. However, ASHRAE class changes in 2008 and 2011expanded the use of chillerless data centers [24–26]. The 2011 ASHRAE classes for data centers are shown in Fig. 2 [26]. 2011 classes A1 and A2 are identical to 2008 classes 1 and 2. Two allowable environmental classes, A3 and A4, are added to expand the environmental envelopes for IT equipment. Data center operators can choose an appropriate class to operate in the most energy efficient mode and still achieve the reliability. These changes bring a good opportunity for free cooling, which is considered to be one of the most prominent ways to make data centers more efficient [27] and has a great potential in data center cooling applications.

Nowadays, free cooling technology of data centers is developing rapidly. The aim of this paper is to provide basic background knowledge and a review of existing literatures on free cooling system of data centers, which is grouped into three categories: airside free cooling, waterside free cooling and heat pipe free

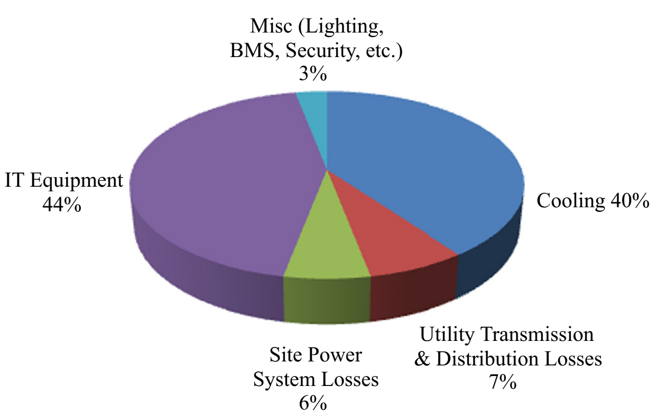


**Fig. 1.** Example of data center energy split [7].

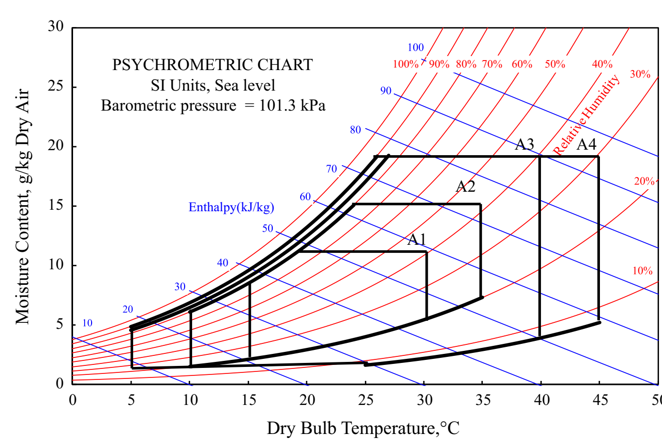


**Fig. 2.** ASHARE environmental classes for data centers [26].

**Table 1**
Different types of data center free cooling systems.

| Category | Type | Feature |
|---|---|---|
| Airside free cooling | Direct | Drawing the cold outside air directly inside |
| | Indirect | Utilizing the outside air through heat exchangers |
| Waterside free cooling | Direct water cooled | Using natural cold water directly |
| | Air cooled | Using air cooler to cool the circulating water |
| | Cooling tower | Using cooling tower to cool the circulating water |
| Heat pipe free cooling | Independent | With no mechanical refrigeration function |
| | Integrated | Integrated with mechanical refrigeration system |
| | Cold storage | Combined with cold storage system |

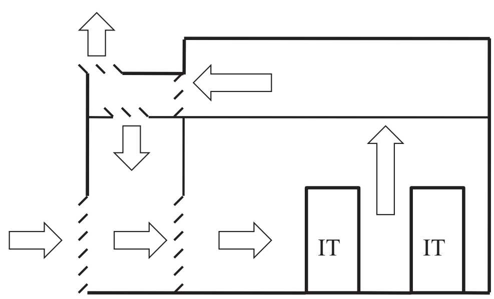


**Fig. 3.** Schematic diagram of direct airside free cooling [30].

cooling. Each of these categories is further classified into different types as shown in Table 1 and discussed in the following chapters. It is hoped that this paper will be helpful for researchers in this field.

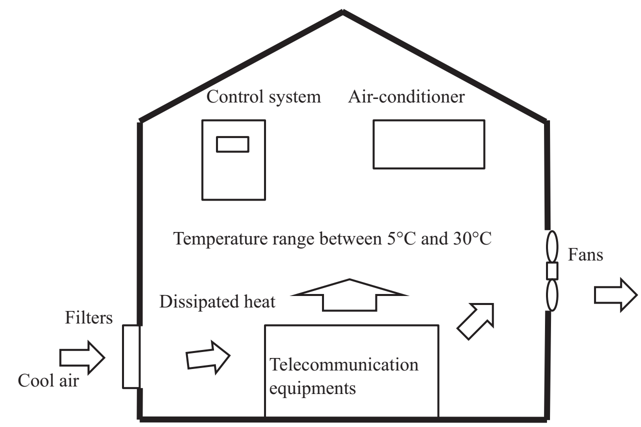


**Fig. 4.** Ventilation cooling technology applied in a typical telecommunication base station [36].

## 2. Airside free cooling

Airside free cooling systems make use of outside air for cooling data centers. In this system, sensors are used for monitoring outside and inside air conditions and temperatures [28]. When the outside temperature is appropriate, airside economizers draw the outside air directly inside or utilize the cooler outside air indirectly by air to air heat exchangers. Airside free cooling is a technology with wide application prospect. According to a recent study, 99% of locations in Europe can use the A2 Allowable range (referring to Fig. 2) and take advantage of airside economizer mode cooling all year, and 75% of North American data centers can operate airside economizers up to 8500 h per year [29]. Airside free cooling can be implemented in direct or indirect ways.

### *2.1. Direct airside free cooling*

Drawing the cold outside air directly into the data center when the outside air conditions are within specified set points is the simplest free cooling method that is called direct airside free cooling, as shown in Fig. 3 [30]. Direct airside economizer is a system of controls, dampers, and fans that changes the facility entirely, or in part, from using compressor-based cooling to bringing in fresh air to cool the IT equipment [31].

Direct air economizer has been used by some data centers and occupies 40% of the total number utilizing free cooling technology [32]. Many IT companies have constructed their own data centers with direct airside economizers. Intel conducted a 10 month free air cooling test in a 10-megawatt (MW) data center, and the result showed an annual US$2.87 million energy savings [33]. Microsoft and Google implemented free air cooling in their new data centers located in Europe in 2009 [34,35].

In order to make full use of the outdoor cooling air, Chen et al. [36] proposed a ventilation cooling strategy for telecommunication base stations. Investigation was based on the field study of a typical telecommunication base station in Guangzhou of China as shown in Fig. 4. The air conditioners were substituted by fans for environmental control when the temperature and humidity of the outdoor air met the cooling requirements. Energy conservation achieved was about 49% by the use of ventilation cooling technology, and the payoff period was less than two years. Further, a control strategy for ventilation cooling technology was provided to guarantee the indoor temperature and humidity and maximize the energy saving [37]. Kumari et al. [38] investigated different configurations for delivery of outside air, including outside air introduced in cold aisles, in plenum close to CRAC units' supply side, at return side of CRAC units, and in hot aisles, to determine the optimal local distribution of the outside air in a non-homogeneous data center. Chang [39] designed a data center with through holes on its housing. When the data center runs, cold air comes into the housing through the holes to cool the heat units inside. Then the heated air is vented out of the housing through the top wall by fans mounted in the housing.

According to the quantitative study conducted by Siriwardana et al. [40] based on hourly weather data of temperature and humidity from 2000 to 2011 for 20 weather monitoring stations across Australia, cities in Tasmania and Southern Australian such as Melbourne and Adelaide have the potential of outside air cooling more than 5500 h per year. They also demonstrated that other than tropical and humid areas such as Darwin and Townsville, data centers in major cities can exploit dry and cool climate for cooling at a sizeable proportion, especially at night during

winter months [40]. Simulation program was used by Lee and Chen [41] to analyze the energy saving potential of direct airside free cooling in worldwide climate zones and they claimed that direct airside free cooling is not applicable in climate zones with a lower dew point temperature for significant humidification cost.

Though direct airside free cooling has the advantage that it does not require pump or tower energy or any steps of heat transfer [42], it has some concerns including introducing humidity disturbance, unwanted particulates, and gaseous contaminants. For a long period, people worried about the risk of equipment failure brought by direct airside free cooling. In recent years, the risk and methods to control it have attracted the attention of scholars. Shehabi [43] and Udagawa et al. [44] claimed that data center environmental control standards were too strict, which could be further relaxed to meet the demand of free cooling. Dai et al. [45,46] reported the risk of drawing cold air directly into data centers and approach to reduce it. Studies of eight data centers in California by Shehabi et al. [47–49] showed that concentration increase of particle pollutants brought by airside economizers did not exceed the ASHRAE specified level and could even be neglected when air filters of good performances were also used. Meanwhile, according to their investigations, data centers with airside economizers could also achieve humidity control. Coles et al. [50] conducted a survey on the effect of gaseous contaminants for selected data centers situated in the US and Indian cities including San Francisco, Los Angeles, Dallas, Atlanta and Bangalore. They reported that data center operators in these regions should not be concerned about environmental gaseous contaminants causing high data center equipment failure rates even when airside economizers were used.

The above findings show that the effect of contamination in some regions is slight while it is not always true for other regions. Yin et al. [51] studied the feasibility of ventilation cooling for telecommunication base stations in China. Experimental results showed that it was not suitable to use the ventilation cooling system in Harbin and Beijing for their high falling dust. For Shanghai, Kunming and Guangzhou, the period of using ventilation cooling system was 3949 h, 6082 h and 4089 h, respectively. Therefore, the risk of free cooling depends greatly on the local environment, however, we should recognize that direct airside economizers have application prospects at least in a considerable amount of regions.

It is worth noting that when direct air economizer is used, reliable control strategies and sensing devices are needed to control the indoor environment and any significant error may lead to wasteful energy consumption or equipment failure [52].

### 2.2. Indirect airside free cooling

As mentioned above, utilizing direct air economizers will disturb the internal environment of data centers. Indirect air economizers operate through air to air heat exchanger allowing for the transfer of heat with little to no transfer of external air to the internal data center environment.

Kyoto wheel system is a well known example of an indirect air economizer system as shown in Fig. 5 [53]. It includes a rotary heat wheel air to air heat exchanger with a direct expansion (DX) cooling system and controls to manage the system. This allows air supplied to the data center without disturbing the indoor environment, and it can utilize free cooling when available and fall back onto traditional cooling when required. The annualized coefficient of performance (COP) of these systems is at about 8–10, higher than that of traditional cooling systems which is at around the 3.5 mark.

Bao et al. [54] investigated a communication base station equipped with a plate exchanger to discharge excess heat when the outdoor temperature was low enough. The results showed that the plate heat exchanger could cool the station instead of air conditioning for about 5014 h each year, and the corresponding electronic power saving rate reached up to 29%.

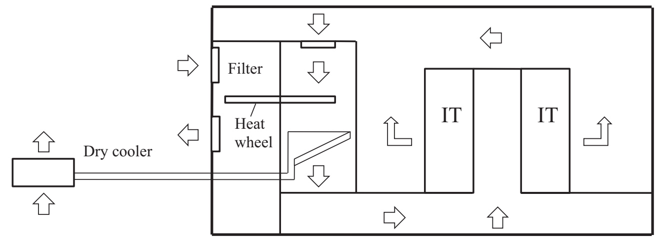


**Fig. 5.** Kyoto wheel system [53].

As with all heat exchangers, a large quantity of contaminants in the air passing through the heat exchanger will accumulate over time, reduce the effectiveness of the heat exchangers and increase maintenance frequency. Moreover, although these systems are very efficient, they need to be quite large, due to the sizeable surface area required to maintain an acceptable pressure drop and heat transfer. The suitability of these systems is limited but can be considered on a case by case basis for suitability.

## 3. Waterside free cooling

Waterside free cooling is a concept that utilizing natural cold source through a cooling water infrastructure so that the free cooling process can be introduced without compromising on the internal environment. Waterside free cooling can be further divided into three types: direct water cooled system, air cooled system and cooling tower system.

### 3.1. Direct water cooled system

In a direct water cooled system, natural cold water is used directly to cool the data center without any steps of heat transfer. Clidaras [55] proposed a data center located on or near an ocean or ocean extension, which was equipped with a closed loop cooling system as shown in Fig. 6. The coolant flows and transfers heat to the seawater through a heat exchanger. Energy from natural motion of seawater is captured and turned into pumping power of cooling pumps.

Due to the significant thermal mass of water, direct water cooled system can maintain a temperature close to the average ambient temperature in 24 h. However, its application is limited for its dependence on natural cold water, so locating data centers on or near an ocean is a good choice. However, the weather and waves of the ocean should be considered which may result in damage to the data centers.

### 3.2. Air cooled system

In an air cooled system, an air cooler is used to cool the water circulating to CRACs when wet-bulb temperature of the outside air is low enough.

A widely seen example is the system with a second coil shown in Fig. 7 [30,53]. The DX CRAC includes an independent second coil that uses the cooling water during economizer mode. When the outside air conditions are within specified set points, the water returns from the dry coolers and flows through a chilled water coil reducing or eliminating the need for mechanical cooling. The downside to this type of system is that when free cooling is not possible, the system operates in traditional DX cooling mode but

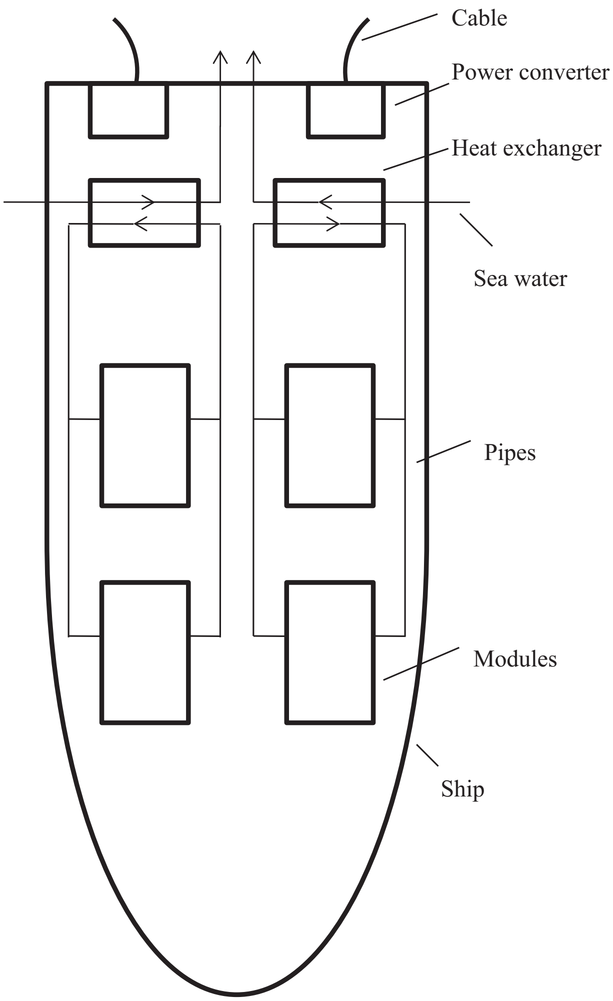


Fig. 6. Data center located on an ocean [55].

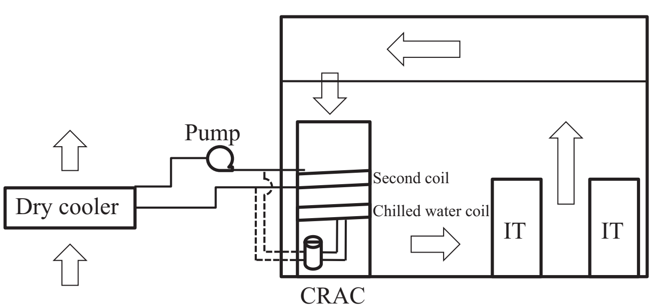


Fig. 7. System with a second coil [30,53].

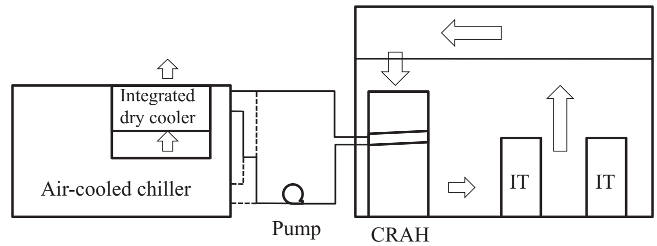


Fig. 8. Air cooled direct expansion chillers with free cooling [30,53].

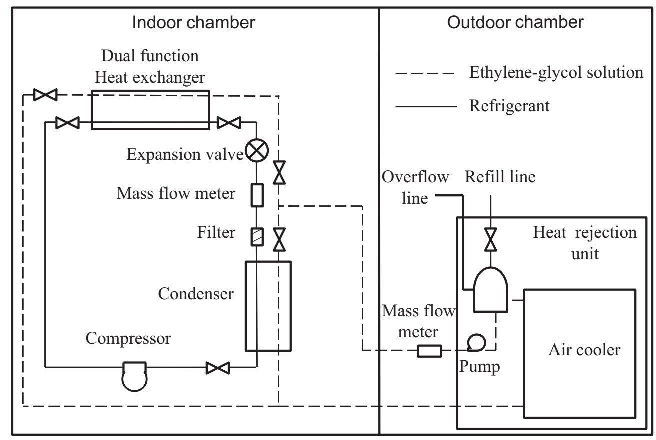


Fig. 9. Schematic of a hybrid refrigeration system [59].

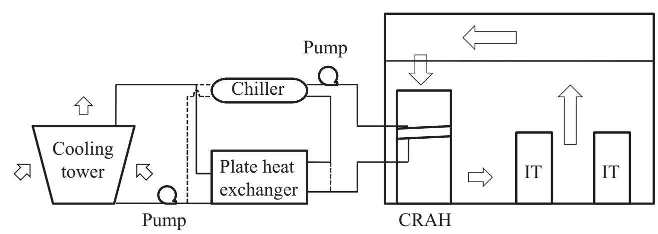


Fig. 10. Chiller bypass via heat exchanger economizer mode [30,53].

with less efficiency than normal, because of the fan pressure and energy consumption increase brought by the additional coil in the air path.

Another example is the system with air cooled DX chillers of free cooling [30,53]. In this system shown in Fig. 8, a dry cooler is integrated in the air-cooled chiller, which can directly cool the data center chilled water when the outside air conditions are within specified set points. This method has a smaller footprint and provides significantly more predictable and efficient economizer mode operation compared to field-assembly of the same components. Moreover, it allows a simple design with the ability to provide redundancy by duplicating chiller units. With the right design, more free cooling capacity can be achieved through the increased surface area by running redundant chillers.

The above two examples are most commonly seen. Some similar designs have been developed based on the improvement of these two systems [56–58].

Choi [59] designed a hybrid refrigeration system including an indoor unit and an outdoor unit as shown in Fig. 9. The hybrid system operates in two modes based on outdoor temperature. At high outdoor temperatures, the hybrid system operates in the vapor compression cooling mode (mode 1). The dual function heat exchanger absorbs the heat generated from the telecommunication equipment, and the condenser disposes of the heat to the ethylene–glycol solution, which goes into the condenser and then returns to the outdoor unit. At low outdoor temperatures (under 8.3 °C), the hybrid system operates in the secondary fluid cooling mode (mode 2). The ethylene–glycol solution enters the dual function heat exchanger and then returns to the outdoor unit, rejecting the heat generated from the telecommunication equipment by the heat exchange between the air and the solution. The COP of the hybrid refrigeration system varies from 2.6 to 3.5 and from 3.2 to 9.0 in mode 1 and mode 2, respectively, when the indoor temperature is 27 °C and the outdoor temperature changes from 16.7 to 35 °C and from 5 to 16.7 °C, respectively. The average COP is higher than that of the conventional vapor compression systems for no operation of compressor in mode 2.

### *3.3. Cooling tower system*

In a cooling tower system, a cooling tower is used to cool the water circulating through CRACs and heat exchangers. Two water loops are needed, a cooling (external) water loop and a chilled (internal) water loop.

Traditional CRAC can be modified into this kind of system by adding a chiller bypass via heat exchanger economizer mode [30,53] as shown in Fig. 10. A secondary water circuit is used to indirectly cool the data center chilled water. When the outside air conditions are within specified set points, pumps move the cooling water through a heat exchanger to cool the chilled water used in computer room air handlers (CRAHs), bypassing the chiller. Partial operation is also allowed when the heat exchanger is in series with the chiller. This kind of system is widely used in large-scale data centers and significant energy savings are achieved.

Carlson [60] proposed a cooling system included a cooling water source and a plurality of on-floor cooling units as shown in Fig. 11. Air handling units that absorb heat from IT equipments, including fans and cooling coils are cooled by internal cooling water. When the system works at free cooling mode, the heat exchanger bypasses the chiller and passes the heat from the internal cooling water to external cooling water, which is delivered to a cooling tower. Based on this system, Hamburgen et al. [61] developed an improved system by replacing the air handling units with modular cooling plants.

Cooling tower free cooling system can be conveniently combined with absorption refrigeration, which can utilize solar energy and waste heat of data centers. High efficiency will be achieved for absorption chillers when utilizing these thermal sources [62]. Absorption solar cooling has been applied in free cooling systems of data centers. Hamann et al. [63] proposed a data center cooling system utilizing free cooling and/or solar cooling as shown in Fig. 12. When the outside temperature drops below a certain value, the data center takes advantage of free cooling and the chiller plant can be bypassed. In addition, heat is generated by solar collector system and the heat drives absorption refrigerator which provides cooling water to the internal water loop. Free cooling can exploit the cooling temperatures during the night when solar energy is not available. With the improvement of performance and simulation model of absorption solar cooling in recent years [64–68], the combination of free cooling and absorption solar cooling is easier to realize than before, which provides the possibility of minimizing the use of chiller plant thereby saving energy consumption. In short, free cooling system combined with absorption refrigeration has good application potential and more attention is worth being paid to this field.

The three kinds of systems are just three means of achieving waterside free cooling and they do not have strict boundaries. We can choose according to the application conditions. They can be converted into each other, for example, a cooling tower system can be converted into a direct water cooled system by replacing the cooling tower with natural cold water source.

The application of waterside economizers was recommended by ASHRAE Standard 90.1 [22]. The analysis conducted by Intel [69] also indicated that waterside economizers were more cost-effective for these projects than the alternative airside economizers. According to the survey of the Green Grid in 2011, waterside economizers are the most widely used economizers in data centers [32].

## 4. Heat pipe system

Heat pipe heat exchanger (including thermosyphon) has superior temperature control features and ability to transfer heat at small temperature difference without external energy, which is suitable for utilizing natural cold source. In 2004, Wilson et al. [70] proposed a loop thermosyphon system for the data center rack-level cooling systems, namely, “Thermal Bus” system. The system collected the heat release of chip through heat sinks, and transferred heat to the air-cooled heat exchanger mounted on the top of the cabinet though a loop thermosyphon [71]. In the same year Khodabandeh [72] designed a thermosyphon loop for components of radio base stations. Though these systems did not use natural cold source, they introduced heat pipe into data center cooling.

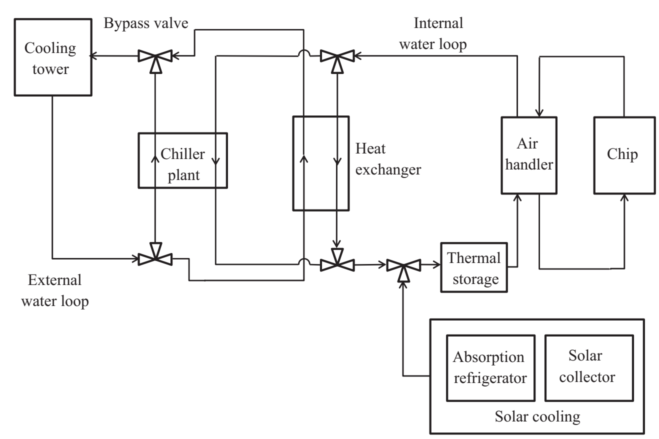


**Fig. 12.** Data center cooling system utilizing free cooling and/or solar cooling [63].

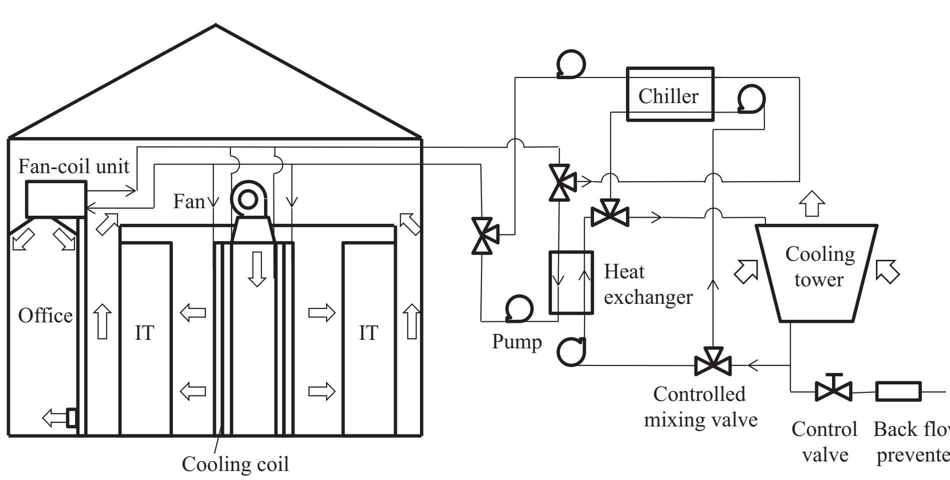


**Fig. 11.** The cooling system designed by Carlson [60].

Ever since, many scholars have conducted research in this area. Heat pipe free cooling system can be further divided into the following three types: independent system, integrated system, and cold storage system.

### 4.1. Independent system

Independent heat pipe system can only cool the data center by heat pipe and has no mechanical refrigeration function. Therefore, it needs a supportive vapor compression refrigeration system as auxiliary when the ambient temperature is relatively high.

Tian et al. [73] developed a heat pipe air-conditioning system for data centers as auxiliary of compressor units as shown in Fig. 13. They further investigated the liquid filled ratio of the heat pipe air conditioning system and reported that the optimal liquid filled ratio was about 80% [74]. According to their simulated results, the average COP was 11.8 during its operating season in the weather condition of Shanghai [75]. Some other heat pipe systems for data centers, including single-pipe connection heat pipe [76], heat pipe with thin long evaporation section [77], heat pipe with pin-shaped fins wound outside vertical heat exchange pipes [78], are similar to this system.

Weber and Wyatt [79] designed a data center utilizing heat pipes as shown in Fig. 14. A number of heat removal systems are coupled to computing racks in the data center. A heat removal system consists of a heat pipe and a heat dissipation mechanism. They extend outside the cooling system compartment through the ceiling. The cold outside air flows through the pressurized plenum and cools the heat dissipation mechanism. This system divides the data center into two spaces so it can contain the heat pipe inside the data center and simultaneously utilize the cold outside air without taking contaminants into the data center. This method was also adopted in the systems designed by Peng [80] and Tozer et al. [81].

Li et al. [82] proposed another heat pipe cooling system for data enters as shown in Fig. 15. When the indoor and outdoor temperature difference was 5–24 °C, the energy efficiency ratio was 3.63–10.64. They reported that it could replace vapor compression refrigeration in winter.

Zhou et al. [83,84] investigated the heat load and energy consumption characteristics of thermosyphon heat exchangers and air conditioning units in an IDC room. The effects of the building envelope and the indoor and outdoor temperatures were also analyzed. The energy consumption of the thermosyphon heat exchanger was only 41% of that of an air conditioner and the annual energy consumption of the IDC room was reduced by 35.4%.

Ekstedt and Johansson [85] designed a radio base station with a loop thermosyphon as shown in Fig. 16. The electronic modules are not cooled by air, instead they are mounted on the loop thermosyphon through a heat conducting wall, which has corrugated contact areas to enhance heat transfer. The heat from the

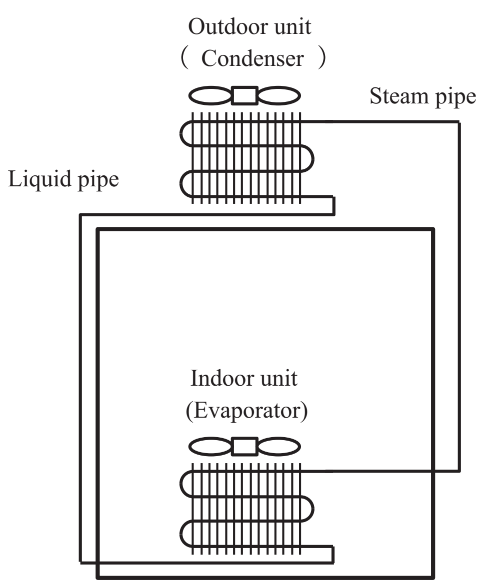


**Fig. 13.** The heat pipe air-conditioning system designed by Tian et al. [73].

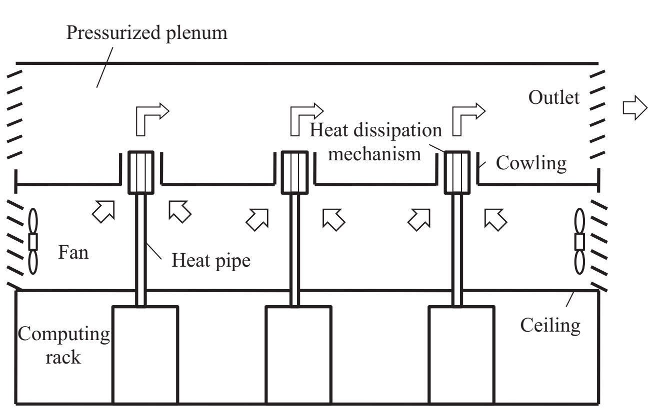


**Fig. 14.** The data center utilizing heat pipes designed by Weber and Wyatt [79].

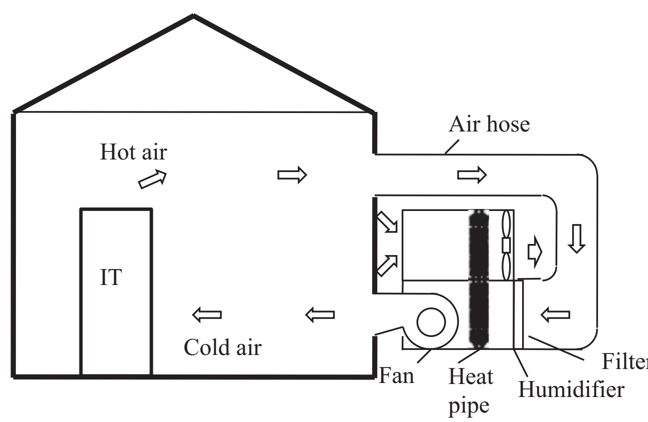


**Fig. 15.** The heat pipe cooling system designed by Li et al. [82].

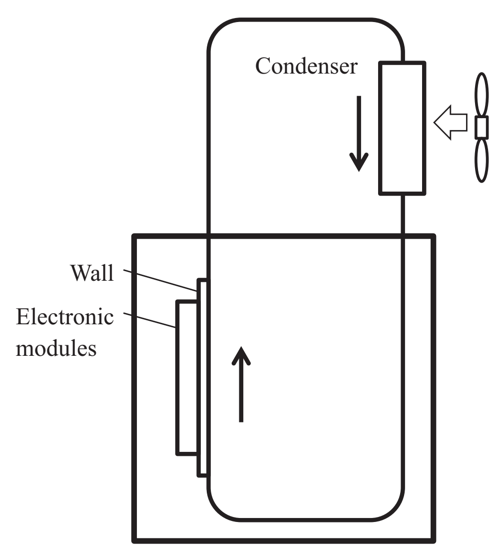


**Fig. 16.** Radio base station with loop thermosyphon [85].

electronic modules is transferred through the wall to the condenser on top of the base station and cooled by the outside air.

Samba et al. [86] designed a thermosyphon loop with a sloping condenser for cooling telecommunication equipments in the outdoor cabinet as shown in Fig. 17. The thermosyphon loop efficiency, the temperatures distributions, the thermal resistance, mass flow rate and heat losses by convection in the walls of the cabinet as a function of heat load were studied. The n-pentane was used as the working fluid and the optimal filling ratio is about 9.2%. The results showed that the maximum heat load of the telecommunication equipment obtained with the thermosyphon loop cooling system was twice as much as that given by the traditional cooling system.

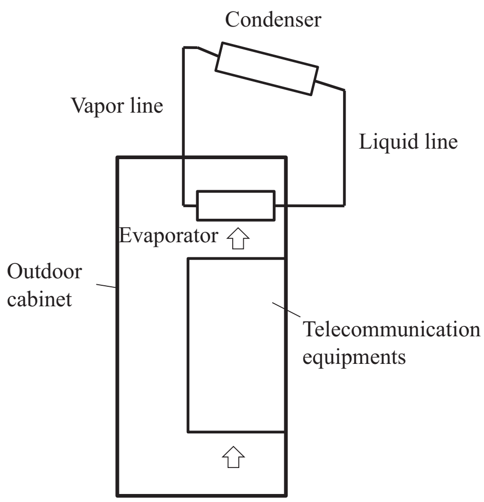


**Fig. 17.** Thermosyphon loop for cooling telecommunication equipments in the outdoor cabinet [86].

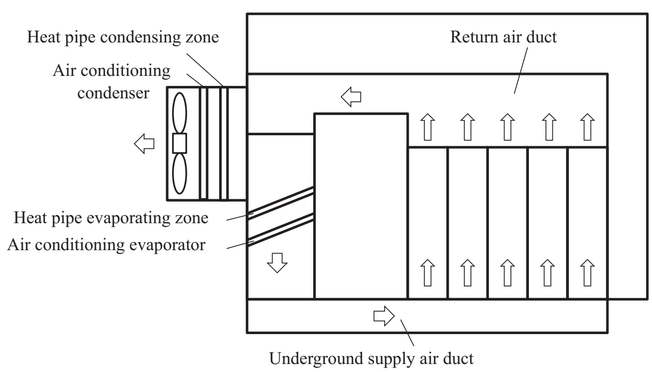


**Fig. 18.** Composite air conditioning system combining a heat pipe exchanger and an air conditioning system [87].

### 4.2. Integrated system

The above studies focused on independent heat pipe units, which need the auxiliary of vapor compression refrigeration. An integrated system can avoid two sets of equipment and reduce the initial investment to a certain extent. Jin et al. [87,88] developed a composite air conditioning system combining a heat pipe exchanger and an air conditioning system as shown in Fig. 18. They reported that when the average air temperature of environment is 20 °C, the air temperature of heat source could be kept within the given range with the heat pipe exchanger. The COP ranged from 4.66 to 13.9, and the average COP value reached 9.05.

Integrated air conditioner with thermosyphon (IACT) also provides an alternative. This kind of system combines the vapor compression refrigeration and thermosyphon in one facility. However, the capacity of the previous IACT in thermosyphon mode is quite small due to high pressure drops [89–91]. Han et al. [92] proposed an improved IACT and applied it in cooling of data centers, as shown in Fig. 19. When the outdoor temperature was lower or the load was small, it worked in the thermosyphon mode, otherwise in the vapor compression mode. Self-operated 3-way valve, new evaporator and different connection pipes were developed, which enhanced the performance by reducing the pressure drop for dual mode and increased the ability and reliability of vapor compression mode. The field tests in mobile phone base stations in different cities in China showed that this system saved about 34.3–36.9% energy than traditional air conditioners. In order to analyze the detailed energy consumption and applicability of IACT under different conditions, a simulation model was further built and verified [93].

### 4.3. Cold storage system

The cooling capacity of heat pipe systems depends greatly on the ambient temperature environment so that it is not stable and lack of reliability. Cold storage system combined with heat pipes can overcome this drawback, especially system with phase change materials (PCMs), which are more suitable for application in

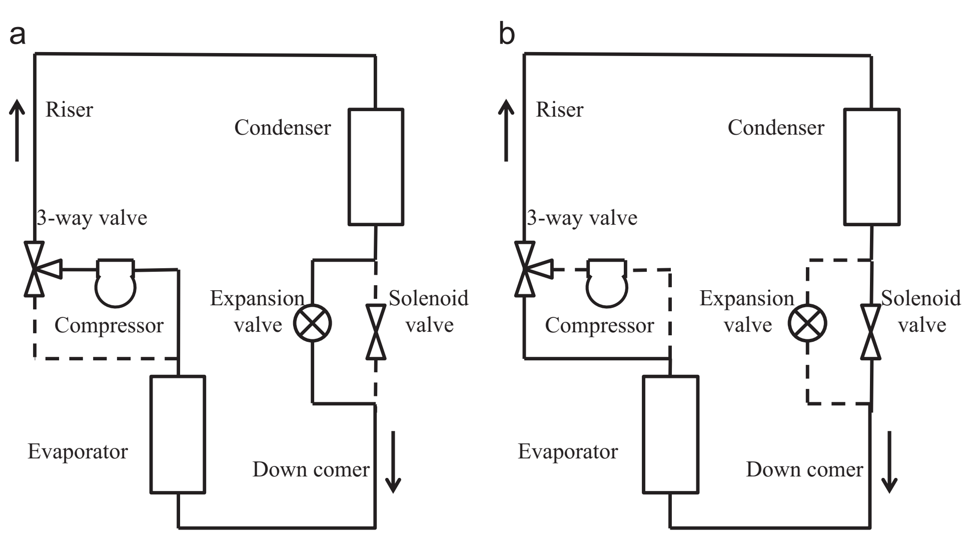


**Fig. 19.** Improved integrated air conditioner with thermosyphon [92].

buildings for higher energy storage density than the sensible storage materials [94]. Sundaram et al. [95] designed a passive cooling system comprising PCM and two-phase closed thermosyphon for telecom shelters, as shown in Fig. 20. The entire unit consisting of telecommunication equipments, thermosyphons and an energy storage unit containing a required number of PCM encapsulated balls immersed in water was kept inside an insulated enclosure. During day time, the ambient temperature ($T_a$) was higher than the temperature inside the shelter ($T_e$) and the heat dissipated from the equipment ($Q$) was stored in the thermal energy storage unit as a sensible heat in water ($Q_w$) and latent heat in PCM ($Q_{pcm}$). During night time, the ambient temperature was lower than the temperature inside the shelter and the stored heat was transferred to the ambient by the thermosyphons. Then the thermal energy storage unit stored sufficient cool energy and it would be available to absorb heat from electronic equipment during day time. It is a highly efficient system for remote areas where there is no power grid and the maintenance is limited. However, upon the results, the capacity of PCM may be not sufficient in some months during the year, thus optimal design is needed to fulfill the heat load requirement of electronic equipments.

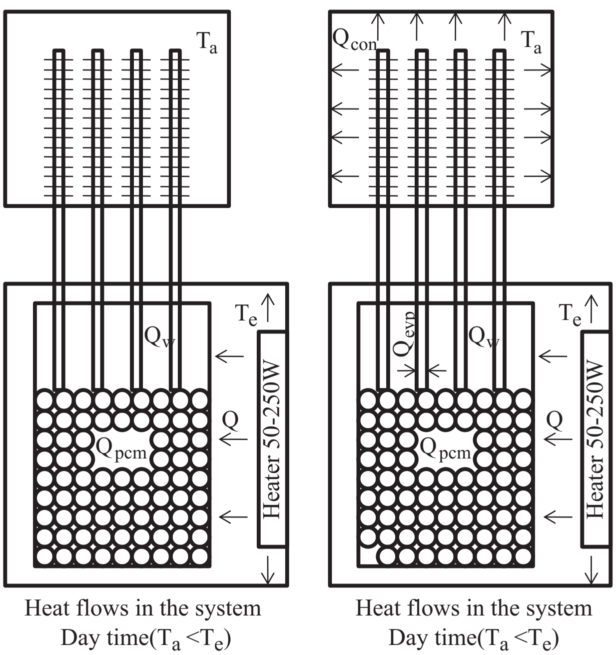


**Fig. 20.** Passive cooling system comprising phase change material (PCM) and two-phase closed thermosyphon [95].

In order to provide sufficient capacity, a chilled-cooling tower system is added to the pipe based cold storage system designed by Singh et al. [96,97] for data centers as shown in Fig. 21. The cold storage provides the chilled water for extracting heat from the rack chipsets via highly effective plate type heat exchanger, which also helps to avoid contamination of the liquid cooled heat sink. The cold storage can be water storage or ice storage. The chiller-cooling tower system is connected to the cold storage and helps to provide extra cold energy to the storage water, when the capacity of the heat pipes is not enough. The downtime of the chiller equipment attributed to the cold energy storage system can save electricity cost.

The above studies show that heat pipe system of data center has good energy saving effect compared to traditional CRACs for its excellent thermal control performance and ability to transfer heat at small temperature difference without external energy. Though it is still in the exploratory stage and has not been widely adopted due to unfamiliarity and reliability concerns, it has great application potential in the future.

## 5. Criteria of performance evaluation

Criteria of performance evaluation for free cooling systems of data centers are necessary for system design. The criteria are summarized as follows.

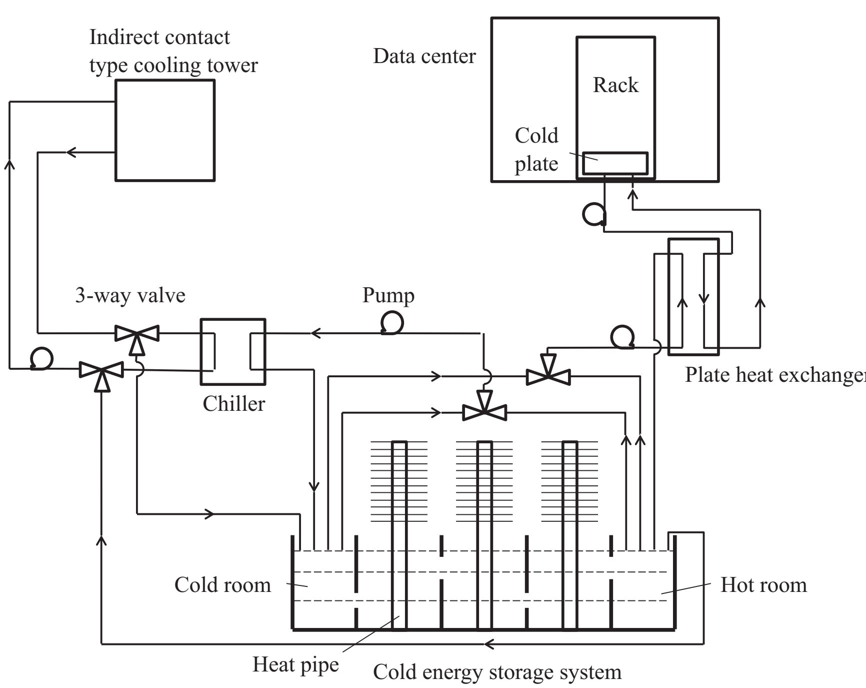


**Fig. 21.** Pipe based cold storage system combined with a chilled-cooling tower [96].

**Table 2**
Innovative and representative free cooling systems of data centers.

| Type | System | Indoor environment disturbance | Need for supportive compression refrigeration system | Energy-saving and cooling effect |
|---|---|---|---|---|
| Direct airside | Chen et al.[36] | Yes | Yes | 49% energy conservation |
| Direct airside | Chang [39] | Yes | Yes | |
| Indirect airside | Kyoto wheel [53] | No | No | Achievable COP of 8–10 |
| Indirect airside | Bao et al. [54] | No | Yes | Up to 29% energy conservation |
| Waterside: Direct water cooled | Clidaras et al. [55] | No | Yes | |
| Waterside: Air cooled | System with second coil [30,53] | No | No | Less efficiency than normal when works in traditional mode |
| Waterside: Air cooled | System with air cooled chillers [30,53] | No | No | Smaller footprint and more cooling capacity can be achieved |
| Waterside: Air cooled | Choi et al. [59] | No | No | COP varies from 2.6 to 3.5 and from 3.2 to 9.0 in mode 1 and mode 2 |
| Waterside: Cooling tower | System with chiller bypass via heat exchanger [30,53] | No | No | Wide application and significant savings |
| Waterside: Cooling tower | Carlson [60] | No | No | |
| Waterside: Cooling tower | Hamburgen et al. [61] | No | No | |
| Waterside: Cooling tower | Hamann et al. [63] | No | No | |
| Heat pipe: Independent | Tian et al. [73] | No | Yes | Average COP of 11.8 |
| Heat pipe: Independent | Weber and Wyatt [79] | No | Yes | |
| Heat pipe: Independent | Tozer et al. [81] | No | Yes | |
| Heat pipe: Independent | Li et al. [82] | No | Yes | Achievable COP of 3.63–10.64 |
| Heat pipe: Independent | Ekstedt and Johansson [85] | No | Yes | |
| Heat pipe: Independent | Samba et al. [86] | No | Yes | Doubling the maximum heat load |
| Heat pipe: Integrated | Jin et al. [87] | No | No | Average COP of 9.05 at ambient temperature of 20 °C |
| Heat pipe: Integrated | Han et al. [92] | No | No | 34.3–36.9% energy conservation |
| Heat pipe: Cold storage | Sundaram et al. [95] | No | Yes | Does not require power but the capacity may be not sufficient for some regions |
| Heat pipe: Cold storage | Singh et al. [96] | No | No | Saving 3 million$/year for a datacenter with heat output capacity of 8800 kW |

Indoor environment disturbance: If the outdoor air mixes with the air inside the data center in a free cooling system, the outside air quality will affect the indoor air quality and result in availability risks.

Need for supportive compression refrigeration system: Though data centers can be adequately cooled simply by free cooling in some cold regions, for most of the regions in the word, a free cooling system will need for a supportive refrigeration system if not integrated with compression refrigeration.

Energy-saving and cooling effect: An important criterion of all cooling systems.

Other criteria such as footprint, initial investment and life expectancy also need to be considered while they are not the focus of this paper.

In order to help newcomers and scholars acquire the latest developments in this area, an overview of innovative and representative systems considering these criteria is given in Table 2.

## 6. Conclusions

Expansion of the number of data centers brings a great challenge to energy saving. Traditional vapor compression refrigeration system consumes a lot of electricity and cannot meet the sustainable utilization requirement of energy. Free cooling of data centers is a technology that utilizes natural cold source, making it possible to not only save the energy consumption of data centers but also achieve the purpose of cooling in a renewable and sustainable way.

Free cooling of data centers can be divided into three categories: airside free cooling, waterside free cooling and heat pipe free cooling. Advancements and characteristics of each are summarized and discussed. Among the three categories of free cooling systems, heat pipe system has good energy efficiency and cooling capacity due to its ability to transfer heat at small temperature difference without external energy. Also, it has no disturbance on the indoor environment and can be integrated with compression systems. Though it has the shortest history, it shows a great application potential.

The criteria of performance evaluation for free cooling of data centers and an overview of free cooling systems based on these criteria are demonstrated in order to help researchers acquire the latest developments in this area. It is hoped that this review will help increase awareness and spur efforts in exploring and maximizing the potential of free cooling of data centers to realize greater energy efficiency.

## Acknowledgement

The authors gratefully acknowledge the financial supports from the National Natural Science Foundation of China (No. 51006113) and National “Twelfth Five-Year” Plan for Science & Technology Support of China (2012BAA13B03).

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